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Ecological Considerations in Pesticide Risk Assessment for Aquatic Ecosystems*

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Abstract: Risk assessment of pesticides for aquatic ecosystems is typically based on comparisons of exposure and effect concentrations at a variety of levels (tiers). At the highest tier, effects assessment can involve generating data under field conditions, typically in mesocosm experiments. However, interpreting the ecological significance of effects measured in these studies can be difficult because ecological factors can influence the outcome of perturbations in the real world. The influence of ecological factors is not readily addressed experimentally and so a strategic modelling approach is proposed which may aid in defining acceptability of effects.

Key words: aquatic risk assessment, pesticides, mesocosm, ecology

1 INTRODUCTION

In this paper, the interpretation of mesocosm data in pesticide risk assessment with regard to determining acceptable levels of effect will be discussed. An acceptable effect can be defined as a measurable difference between untreated and pesticide-treated mesocosms which is of little ecological significance (see Section 4 below for further discussion). Modelling approaches which may provide guidance on the acceptability of effects under different environmental conditions will be described.

Procedures for assessing potential risk from the use or release of pesticides and other organic chemicals to aquatic environments are reasonably well-established with various national and international regulatory authorities. Although differing in certain details, these are mostly based on a similar general concept i.e. that potential risk can be described by comparison of concentrations which elicit effects on organisms with concentrations which are predicted to occur in the environment for a specific use pattern. For pesticides, products are considered to present no risk if the ratio of these two figures is less than a pre-determined safety or application factor, usually between 10 and 100 for acute assessments and between 1 and 10 for chronic.

This approach is conservative; effect concentrations are generated under worst-case exposure conditions in the laboratory and environmental concentrations are predicted under extreme use and exposure scenarios. Therefore, if a compound is determined to present no

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potential risk from this preliminary assessment, adverse impacts are unlikely to occur during use. But the converse is not necessarily true—if a compound is identified as presenting a potential risk in preliminary assessments, it does not inevitably mean there will be a risk in reality because the process is conservative. This is because other factors (changes in bioavailability in the environment, interspecies differences in sensitivity, etc.) not included in the initial evaluation could significantly mitigate potential risks.

If a potential risk is identified from preliminary assessments, two courses of action can be taken: either management measures can be used to reduce exposure by limiting use patterns (e.g. by lowering label use rates and numbers of applications, or by imposing buffer zones between the use area and water courses) so that the potential for the chemical entering the environment is reduced or by generating additional laboratory data on potential effects and/or exposure to provide a more realistic quantification of risks, usually to account for a mitigating factor not included in the preliminary assessment. At the extreme of experimental complexity, this latter option also includes generating data under field conditions, usually through the use of outdoor microcosms or mesocosms—experimental systems which attempt more realistically to simulate ecological and chemical fate processes and therefore produce a better representation of the likely environmental effects of the chemical.

2 INTERPRETING 'EFFECTS' IN MESOCOSM STUDIES

There has been a great deal of debate concerning the use of microcosm and mesocosm studies in pesticide risk assessment, particularly with regard to the experimental design and interpretation of such studies.[1,2] Mesocosms are designed to measure differences (often by analysis of variance) between control and treated mesocosms for a variety of different variables. Interpreting the ecological importance of such differences can be difficult and requires consideration of a number of important factors:

2.1 Recovery from perturbation

Although impacts may be observed on certain organisms during a study, they may subsequently recover during the course of the experiment. Some consideration should be given to the duration of a difference before it is considered ecologically significant. This will also vary for different types of organisms. Even what may appear as relatively easily interpretable endpoints, such as differences in abundance (i.e. population reductions), may not be so obvious depending on the life history of organism. The mortality of an individual may be important for an organism with low reproductive rates and a long life-cycle, but may be of little significance to a fecund species with a short generation time.

2.2 Relevance to other aquatic ecosystems

Measuring effects in one type of experimental system may provide useful information for determining what happens in that specific system. However, it may be difficult to interpret those effects in relation to other types of ecosystem. It has been suggested[3] that differences in climate, size, location, etc., may mean that results from one study may not always be readily extrapolated to all other ecosystems. In many cases, mesocosms may provide an ecological worst-case because of their relatively small size and isolation.

2.3 Influence of experimental design

For analysis of variance, whether a significant difference is detected between treatment and control depends on the sensitivity of the experiment; two experiments identical but for differing amounts of experimental noise (error) could give apparently very different results. A 'noisy' experiment is less likely to detect differences than a less variable study. Consequently, if the conclusions of the studies (effect or no effect) were based on number of significant differences alone, then the conclusions reached may be erroneous. At present, there are no guidelines for what constitutes acceptable levels of variation within a mesocosm study and this decision is often delegated to 'expert judgment'. Furthermore, noise can vary enormously between different sampling events.

For every statistical comparison, there is always a defined probability that a difference will be designated as significant, when in fact it is not (Type II error or false positive when there is a null hypothesis of no effect). For example, at the 0·95 significance level, there is a 0·05 probability of measuring a false positive. Mesocosm studies typically evaluate a very large number of variables over a relatively long time period, which has implications for interpretation, since the number of false positives will increase proportionally with the number of measurements. It is apparent, therefore, that a measured statistical difference may not always be ecologically important.

Uncontrollable chance events which Hurlbert[4] defines as 'demonic intrusions' can also lead to differences between control and treatments which may not necessarily be related to treatment concentration, often resulting in an apparent lack of dose response. The results of such experimental 'catastrophes' are usually reasonably apparent. However, more subtle intrusions such as minor environmental gradients may go undetected.

3 AN EXAMPLE WITH THE PYRETHROID INSECTICIDE CYPERMETHRIN

In order to illustrate some of the difficulties that can arise from interpreting mesocosm studies, data on the effects of cypermethrin on two peracarid crustacean families, the Gammaridae and Asellidae, will be described. Cypermethrin is a pyrethroid insecticide which is used in a wide variety of crops. There is a substantial amount of information on the compound, including a number of mesocosm and large-scale field studies which have been carried out under realistic agricultural conditions.[5] Cypermethrin is of high inherent toxicity to Peracarida, with acute toxicity values in the region of 0·01 μg litre^{-1} (Zeneca, unpublished, and Ref. 6). Depending on the crop and use rate, instantaneous worst-case predicted environmental concentrations from agricultural uses are estimated in the region of 0·01–0·1 μg litre^{-1}. Preliminary risk assessment of cypermethrin would therefore suggest that there is potential for effects on Peracarida. Additional laboratory studies have shown,[7] however, that, due to the rapid adsorption of cypermethrin to sediment and other organic matter (organic carbon partition coefficient (K_{OC}) is approximately 200 000), exposure of crustacea in the field is likely to be reduced substantially, by around 300 times. This information indicates that the preliminary risk assessment overestimates the potential risk of cypermethrin, such that investigation of effects under more realistic conditions is likely to indicate that potential risk will be greatly mitigated.

A mesocosm study performed at exposure rates similar to those that might be expected from agricultural spray drift (1%), investigated impacts on crustacea in 25-m^3 mesocosms.[8] In this study there were significant reductions in both Asellidae and Gammaridae. There were indications that the Asellidae may have been beginning to recover by the end of the study, but Gammaridae were eliminated from the treated mesocosms. The results may seem fairly unequivocal—statistically significant effects were observed on both taxa and the apparent elimination of Gammaridae from the mesocosm could certainly be regarded as of potential ecological significance. But how representative are these data of natural ecosystems and how relevant are they to other types of ecosystem? Ecologically important processes such as immigration from other water bodies and recolonisation from unaffected sites within the water body may not have occurred in the these experimental systems at rates that would occur in nature.

Further doubt is shed on the interpretation of these effects by examining data from larger-scale field studies. In a series of experiments which aimed to simulate realistic agricultural exposure to cypermethrin,[9,10] several natural water courses containing Peracarida have been studied. These studies indicated that additional processes are occurring which may not have been effectively simulated in the mesocosm study. In a study in a farm ditch neighbouring a cypermethrin application,[9] effects were apparent on Gammaridae close to the application area, but recovery occurred very rapidly (in contrast to the mesocosm study), probably from recolonisation from unaffected sites. In another study on several farm ponds to which cypermethrin was applied[10] interpretation became even more difficult when comparing several ponds, since each appeared to respond in a different way. It is clear from these data that very different 'effects' can be observed on Asellidae depending on the type, size and location of the ecosystem in question and its condition at the time of perturbation.

4 WHAT CONSTITUTES AN UNACCEPTABLE EFFECT?

The data described above demonstrate that, to be able to interpret results from mesocosm and field studies, some definition of what constitutes an effect of ecological importance is required. Aquatic ecosystems are diverse and contain organisms which are related to target organisms of crop protection compounds (e.g. arthropods for insecticides, algae and macrophytes for herbicides). Thus, depending on the specificity of the compound to a particular taxon, if there is potential for exposure, then under certain conditions there may be potential for some sort of effect. But having reached the higher tiers of risk assessment associated with mesocosm studies, we have already identified that there may be potential for some effects under certain conditions. In order to be able design an effective study, it is necessary to specify what degree of effect is acceptable for various endpoints. This clearly cannot be simply prescriptive and depends on the objective of the risk assessment. One could consider several different potential objectives for the risk assessment:

- Maintaining biodiversity—ensuring that there are no species extinctions (although it should be recognised that local extinctions are a natural, albeit usually slow, process, associated with species ranges and environmental change);
- Maintaining a certain degree of functionality—e.g. production of a certain biomass of invertebrate food species for fisheries;
- Protecting a certain type of habitat from degradation (wetland, areas of outstanding natural beauty, sites of special scientific interest);
- Protecting rare, threatened or endangered species.

These are clearly not trivial considerations and involve not only scientific considerations, but aesthetic, economic (efficient food production) and political (environmental quality objectives) concerns. It should

also be remembered that pesticide risk assessment should not be viewed in isolation but should also include a benefits evaluation against which any potential environmental cost can be balanced.

To help overcome some of this complexity, it would clearly be helpful if ecotoxicologists could provide a scientific framework for guiding such decisions. With an objective of maintaining biodiversity, for example, this would involve developing approaches that could identify scenarios of perturbation which would describe conditions under which all species would persist and also identify those cases where perturbation may lead to the extinction of a species within a specific region. The development of such a management tool would enable risk assessors and managers to identify which uses of pesticides would be acceptable, even given the broad range of objectives described above.

5 MODELLING APPROACHES

Developing such guidance on the ecological acceptability of perturbation is a considerable undertaking. A large number of factors will determine the persistence of populations of aquatic organisms after exposure to pesticides. Although estimates of exposure and effect concentrations are useful, they are often insufficient alone to predict adequately the consequences of pesticides on a given species. In order to make accurate predictions of population persistence, other factors should be considered, including:

- The spatio-temporal dynamics of the organisms (e.g. intrinsic rate of increase, carrying capacity, immigration, mobility, position in the habitat);
- The spatio-temporal dynamics of the chemical perturbation (e.g. timing, magnitude, duration, frequency, diffusion, decay);
- The overall susceptibility of other species in the ecological community (e.g. competitors, predators, parasites, symboints).

Accounting for all of these interacting factors simultaneously is a huge challenge. However, by extrapolating the results of investigations of short-term dynamics in small-scale experimental systems, we can nevertheless make some coarse predictions. The process of extrapolation in arriving at these predictions is of fundamental importance, not least because we can never hope to evaluate directly the consequences of chemical perturbation for every species in every form of aquatic habitat. Formal mathematical and computer modelling is perhaps the most objective and reliable tool for extrapolation, although even this approach is not without its drawbacks. For instance, ecological models are notoriously poor at accurately predicting quantities such as population size, and the behaviour of some of the more complex ecological models can be as difficult to understand as the real world. Nevertheless, while modelling is not a substitute for laboratory research, it is the only affordable, ethical and objective way of predicting the large-scale ecological impacts of certain chemicals.

How can such modelling approaches be developed? Top-down or ‘holistic’ models are generally capable of more accurate forecasts than bottom-up, reductionist models. For instance, by analyses of current experimental databases, it may be possible to identify those combinations of ecological life-history and habitat attributes which make aquatic organisms susceptible to certain types of pesticide. Thus, for example, with enough experimental data it might be possible to make a probabilistic estimate of the likelihood of a given species becoming extinct under a particular set of conditions, based on what is already known. Besides predictive power, holistic models are popular because they can be easily applied and are not based on unreliable theorising. The problems with holistic models are that they usually require extensive data (which increase dramatically with the number of factors considered), they give no indication of cause *per se*, and they are not easily extended to ranges of factors outside the range of data included (they are better at interpolation than extrapolation in the strict sense of the word).

A complementary method to holistic modelling is the reductionist approach, which aims to develop predictions based on more general ecological principles. Reductionist models can be conveniently classified into *tactical* (detailed models aimed at accurate forecasts) and *strategic* (general formulations aimed at generating broad properties) approaches.[11] In many respects the reductionist approach to bridging the gap between experiment and prediction is preferable. For instance, the formalisation of general principles helps us to identify hidden assumptions that we may hold, it serves as a framework for testing causal relationships and it does not rely as heavily on interpolation.

Most reductionist ecotoxicological models have concentrated on a limited number of well-studied organisms and tried to relate physiological changes in individuals to changes in the population—a tactical approach. However, without large amounts of physiological data on a very wide range of species, the applications of this approach are limited. Since we wish to maintain a general approach (identify types of organisms of risk under certain pesticide uses), then strategic models are more appropriate. Recently, there has been some progress in formulating strategic reductionist models of the impact of xenobiotics on terrestrial invertebrates[12,13] and freshwater species (for example see Fig. 1). Figure 1 shows that by the use of relatively simple ecological relationships, such as that between the rates of immigration and reproduction (e.g. the Euler–Lotka equation), general principles of likely

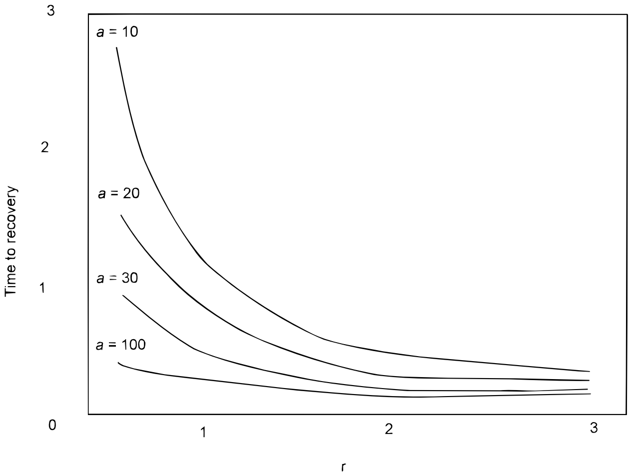

Fig. 1. Relationship between time to recovery from perturbation with reproductive rate (*r*-number of offspring reaching reproductive status per unit time) and immigration rate (*a*-number arriving per unit time) derived from the Euler–Lotka equation (T. Stickland & T. Sherratt, unpublished). Values for *r* and *a* are hypothetical and are used for illustrative purposes.

recovery of organisms of different life history traits can be defined. For organisms with high reproductive rates (increasing *r* on Fig. 1), the rate of immigration (increasing *a* on Fig. 1) is less important in determining the rate of recovery than for those with low reproductive rates. When reproductive rate is low, immigration will be critical to the rate at which a population recovers. This may seem an obvious conclusion, yet the implication at the landscape scale may be extremely important, when one considers that immigration rates will be greatly dependent on the degree of isolation of the ecosystem and the availability of recolonising organisms from neighbouring habitats. The great benefit of the strategic approach is that it should allow us to make quantitative generalisations for organisms with similar life-history strategies in particular habitats.

In common with most ecotoxicological theory, the complete set of models that we are developing will integrate three classes of information: chemical fate (predicted spatial and temporal profile of chemical), exposure (predicted spatial and temporal coincidence of population and chemical) and toxicity (predicted demographic changes in the population as a result of a range of chemical concentrations). Models are most trustworthy if it can be demonstrated that they are valid under specified conditions. An extensive validation programme will be required which will involve surveying existing databases as well as manipulations of outdoor experimental pond systems to mimic the influence of a chemical perturbation and different recovery scenarios. At this early state of development, the models will be viewed as successful if they are simply better at ranking the overall susceptibility of aquatic species to a chemical than a rank based on exposure and effect concentrations alone.

6 CONCLUSIONS

Although mesocosm and field studies are regarded as the ultimate level of aquatic assessment for pesticides, there can be difficulties with interpreting the effects observed in these systems and extrapolating them to the wide range of scenarios that may occur in the real world. In order to be able to understand whether ecologically important effects may occur, it is necessary to understand more than the susceptibility of the organism and its exposure to the pesticide. Ecological factors can play a significant role in either mitigating or enhancing the potential impacts of a pesticide perturbation. Understanding the importance of these for a chemical under a wide variety of situations is clearly beyond the scope of traditional experimental techniques. However, ecological models offer a technique which may allow us to formalise the principles by which these factors affect the overall risk of a pesticide to the aquatic environment. Of the available modelling approaches, reductionist strategic techniques seem to offer the greatest potential because they can be used to develop rules about the huge variety of organisms that exist in the real world, based on making generalisations about organisms with similar life-histories. Only by formalising these general principles will it be possible to understand fully whether a particular organism in a certain habitat is likely to be affected by a toxicant perturbation. Once such models are developed, extensive experimental validation will be required.

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REFERENCES

1. Hill, I. R., Heimbach, F., Leeuwangh, P. & Matthiessen, P. (eds), *Freshwater Field Tests for Hazard Assessment of Chemicals*. Lewis Publishers, London, 1994.
2. Graney, R. L., Kennedy, J. H. & Rodgers, Jr J. H. (eds), *Aquatic Mesocosm Studies in Ecological Risk Assessment*. Lewis Publishers, London, 1994.
3. Crossland, N. O., Heimbach, F., Hill, I. R., Boudou, A., Leeuwangh, P., Matthiessen, P. & Persoone, G. (eds), *Summary and Recommendations of the European Workshop on Freshwater Field Tests* (*EWOFFT*). SETAC-Europe, 1992.
4. Hurlbert, S., Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr.*, **54** (1984) 187–211.
5. Hill, I. R., Shaw, J. L. & Maund, S. J., Review of aquatic field tests with pyrethroid insecticides. In *Freshwater Field Tests for Hazard Assessment of Chemicals*, ed. I. R. Hill, F. Heimbach, P. Leeuwangh and P. Matthiessen. Lewis Publishers, London, 1994, pp. 249–72.

6. Hill, I. R., Aquatic organisms and pyrethroids. *Pestic. Sci.*, **27** (1985) 429–65.
7. Hamer, M. J., Maund, S. J. & Hill, I. R., Laboratory methods for evaluating the impact of pesticides on water/sediment organisms. *Brighton Crop Protect. Conf. Pests Dis.* **2** (1992) 487–96.
8. Farmer, D., Hill, I. R. & Maund, S. J., A comparison of the fate and effects of two pyrethroid insecticides (lambda-cyhalothrin and cypermethrin) in pond mesocosms. *Ecotoxicology*, **4** (1995) 219–44.
9. Shires, S. W. & Bennett, D., Contamination and effects in freshwater ditches resulting from an aerial application of cypermethrin. *Ecotox. Env. Saf.*, **9** (1985) 145–58.
10. Crossland, N. O., Shires, S. W. & Bennett, D., Aquatic toxicology of cypermethrin. III. Fate and biological effects of spray drift deposits in fresh water adjacent agricultural land. *Aq. Tox.*, **2** (1982) 253–70.
11. Nisbet, R. M. & Gurney, W. S. C., *Modelling fluctuating populations.* John Wiley & Sons, Chichester, 1982.
12. Sherratt, T. N. & Jepson, P. C., A metapopulation approach to modelling the long-term impact of pesticides on invertebrates. *J. App. Ecol.*, **30** (1993) 696–705.
13. Brown, R. A. & Sharpe, J. C., Interpreting the results of terrestrial impact studies with references to modelling an ecologically significant impact. In *Field Methods for the Study of Environmental Effects of Pesticides.* BCPC Monograph No. 40, ed. B. D. Greaves, B. D. Smith and P. W. Grieg-Smith, BCPC Publications, Thornton Heath, 1988, pp. 137–45.